California's Water Future

Hydrogeological Report on the Risks to the Medicine Lake Volcano Aquifers Associated with Geothermal Development

Robert Curry,[1] March 2014

Introduction

The Medicine Lake Volcano, a remote very large Cascade volcanic complex, that lies northeast of Mt. Shasta in northeastern California, is proposed for extensive geothermal electric energy development. The total volume of water stored in the underlying aquifer of the Medicine Lake Volcano is 20 to 40 million acre-feet, which is the same order of magnitude as California's top 200 reservoirs (42 million ac-ft). This high quality groundwater emerges as the Fall River Springs (FRS), the largest spring system in the state, at the rate of 1 million to 1.4 million acre-feet each year. Almost half of the drought period monthly total flows from the Pit River to Shasta Lake (Freeman, 2007) are from this remarkable groundwater reservoir that comprises a major portion of California's available water supply. It ultimately flows from the Sacramento River into the California Aqueduct to be carried to the farthest reaches of Southern California. Based on current data, we believe as much as 80 percent of the precipitation in the Medicine Lake Highlands may recharge groundwater in most water-years to feed directly to the 16 km-wide Fall River Springs.

The great broad shield volcano itself is the largest of the Cascade-area volcanoes and covers about 850 square miles (Donnelly-Nolan, 2008). The Medicine Lake Highlands (MLH) has been defined for purposes of that report as the area above the 6680-foot elevation of Medicine Lake itself. The highlands are about 20 miles in circumference and about 6 miles wide in an east-west direction and 4 miles wide from north to south. The Medicine Lake Caldera is the area within that summit-elevation volcanic feature that represents the rim of the crater-like ring around the Medicine Lake Volcano summit (see Figure 1).

This report focuses on the technical aspects of geothermal development as they pertain to California water resources. It is intended to be considered in conjunction with any federal, state, or county evaluation of either expanded or newly proposed geothermal development in the Medicine Lake Highlands. It particularly focuses on the risks for California water supplies through the linkages of Medicine Lake Volcano with the Fall River Springs, Pit River, McCloud River, Shasta Reservoir, and California State Water Project and Central Valley Project water sources from the Upper Sacramento River System.

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This report makes specific recommendations to:

1) develop the necessary baseline information on sources of spring-flow;
2) identify opportunities and risks of shallow groundwater contamination and cross-contamination from the proposed acid-treated and hydrofractured geothermal production zone rock to shallow groundwater; and
3) conduct pre-project research and analysis to help resolve conflicting data that suggest leakage of volatile components from the geothermal reservoir to surface aquifers.

The enormous value of the groundwater reservoir that supplies the Fall River Springs is compared to other, less reliable, supplies including the California State Water Project and other western states water storage facilities to demonstrate the value of Medicine Lake Volcano's passive, gravity-fed, pristine water to the entire State of California.

Importance of Medicine Lake Highlands to California Water Supplies

Surface volcanic rocks of the Medicine Lake Highlands are porous and readily absorb the copious high-elevation regional snowmelt. This snowmelt cumulatively contributes to an estimated 20-40 million acre-feet or more of stored groundwater in the Medicine Lake Volcano area.[2] That snowmelt apparently percolates rapidly along the flanks of the volcanic mountain complex to accumulate as shallow groundwater (the shallow aquifer of Weiss, 1997). The Medicine Lake volcano shallow groundwater recharge gives rise to California's largest spring-water system at FRS. That 16-km wide zone of springs becomes the Fall River flowing into the Pit River and joins the upper Sacramento River at Shasta Lake Reservoir. The exact hydrologic boundaries of the MLV and the eastern McCloud River tributaries are poorly understood, and are further discussed under Research Recommendations below.

Unknown to most California water users, the FRS flows are among the largest in the world and provide an enormously important baseline quantity of California's reliable water flows (Manga, 2001). Because it takes 20 years or more for some of the Medicine Lake Highlands' snowmelt to emerge at FRS and become the Pit River, it follows that the volcanic aquifers of Medicine Lake Volcano that flow by gravity alone into California's water resource system provide an enormous free reservoir of pristine drinking water that is always available and that buffers drought and surplus resources for the entire state (Freeman, *op cit*, 2007).

The Fall River Springs discharge 1,000,000 to 1,400,000 acre-feet of water each year and all of it is captured and made available to California water users. No one has to operate that underground reservoir, and similarly no one protects it. For comparison, one should note that the entire statewide California State Water Project (SWP) deliveries from all the SWP reservoirs have diversions with only an average of 2,400,000 ac-ft (1990-2000). In the

[2] Davisson and Rose, 2014. For comparison California's average April 1 Sierra snowpack volume is 15 million ac-ft, and the capacity of all of California's surface reservoirs is 42 million ac-ft. (Lund, 2011); when full, Shasta Reservoir holds only 4,552,000 ac-ft. Folsom Reservoir if full holds just a little over 1,000,000 ac-ft and even lakes Mead and Powell could release only 26 and 24 million acre feet of water respectively if full. We acknowledge that surface reservoirs can be drained in but a few years while FRS is limited to reliable outflow of about 1 million ac-ft per year.

driest historical year of 1977, the State Water Project could only deliver 970,000 ac-ft but all of it could have come from FRS[3] in that year.

Unlike the widely dispersed and increasingly unreliable Sierra snowpack, the FRS can be expected to continue through times of both drought and surplus precipitation. As previously stated, the shallow groundwater of the Medicine Lake Volcano is available in 1 million ac-ft plus increments each year flowing freely as the FRS. In comparison, the Sierra snowpack is California's largest fresh-water surface source, and has an April 1st annual average of about 15 million ac-ft, which provides about 35 percent of the state's usable water (M. Roos, 2006). That water is available annually but is decreasing as snowpack decreases in response to climate change and/or long-term drought. In contrast, Medicine Lake Volcano groundwater accumulates, and is stored for decades in an aquifer system that is reliable even in times of drought.

The Age of the Water

The volume of the groundwater is a simple function of its age and residence time. The age of the water being discharged from the many sources at FRS has been recently reevaluated (Davisson and Rose, 2014). It was originally determined by the U.S. Geological Survey to be between 40 and 42 years old.[4] A more recent revaluation of geochemical data by Davisson and Rose at the Lawrence Livermore National Labs allows some of the spring water to be as young as 12-20 years. Determination of the age of groundwater requires sophisticated isotopic geochemical analyses.[5] Although two separate federal investigation teams sampled the spring-waters in 1997, the considerable sampling, analysis, and subsequent interpretation of the isotopic data allow differing interpretations. Clearly, water from snowmelt from various places on the volcano must travel by different pathways and emerge at different sampled sites along the 16-km-wide discharge zone that is called Fall River Springs. Because the water discharged to the Fall River at its primary springs has a 12-42 year old radiometric age range depending on sample locations and analytical assumptions, the volume of water in storage above the elevation of the Fall River Springs must comprise at least 12 million to 40 million acre-ft of gravity-fed groundwater [1 million to 1.4 million ac-ft per year X 12-42 years]. That is an enormous reservoir of very high quality fresh water. Placed in context of all the water supplies available in California, the lower estimate of 12 million ac-ft is at least 3 times the capacity of Shasta Reservoir. The three other largest man-made reservoirs in California (Oroville, Folsom and San Luis) together only have a maximum capacity of 6.55 million acre-feet.[6]

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[3] http://www.water.ca.gov/recreation/brochures/pdf/swp_glance.pdf

[4] Robert Mariner, 2006: Mariner's USGS analyses show that: .." the average age for most of the water discharged by the Fall River group of springs is about 42 years. As a small amount of modern precipitation (4 to 5 Tritium Units) must also be present, true circulation times for the older component of the water discharged by the Fall River group of springs must be more than 42 years. This emphasizes that most of the geothermal development monitoring effort should be focused on detecting spills or leaks near the geothermal development sites as it will be decades before chemical changes associated with any accidents would appear in the Fall River springs."

[5] Powers, Laurie, 2003, Age does make a difference, pp. 22-24, Lawrence Livermore National Labs, S&TR (Science and Technology Review Notes), May.

[6] http://cdec.water.ca.gov/cdecapp/resapp/getResGraphsMain.action

Unique Characteristics of Medicine Lake Volcano

The Medicine Lake volcanic complex is geologically young and has erupted at least 17 times in the last 12,000 years (average of once every 700 years). It will certainly erupt in the future (Mariner, 1999; MacDonald, 1966). It differs from many areas of active geothermal development and exploration in that it does not have features such as geysers, hot springs, and surface evidence of high geothermal heat flow. This difference from other California geothermal sites like Coso, Imperial Valley, Mammoth and the Geysers is probably due to high local snowmelt and rapid geologic alteration of shallow volcanic rocks, creating a less permeable clay-like capping on the geothermal reservoir rocks and thus isolating them from the surface. Regional fracturing through the volcanic crater summit area is occurring along north-south alignments, and the surface has been demonstrated to be sinking through east-west tectonic extension (Dzurisin, et al, 2002; Poland, et all, 2006). There is no assurance that this inferred cap is everywhere impermeable or that it will remain impermeable throughout the life of the field.

Threats of Geothermal Development

Hydrofracturing and cross-contamination

Naturally occurring hydrothermal alteration of the hot bedrock creates an immediate impediment to its use for electric power production. This is because the altered bedrock is not permeable so that water cannot be pumped into the ground and circulated to ultimately be withdrawn for steam turbine power production. It is this poor-circulation condition in the geothermal production zone that has led to proposals for development that attempt to utilize hydro-fracturing or acid leaching to create avenues for injected water to be heated and recovered for power generation. The Medicine Lake geothermal resource area has thus become the focus of expenditure of primarily federal funds to try to perfect various modes of Enhanced Geothermal Systems (EGS[7]). The necessity to rely on experimental EGS techniques has raised many concerns from public, land-management and native tribal agencies, as well as fiscal issues, which have delayed full-scale site development. However, project proponents with over 20 years of effort invested are still pursuing development and have proposed a nearly fivefold increase of power production compared to that originally assessed in the mid-1990's EIR/EIS.[8] There are currently no existing Medicine Lake power plants, although the first deep well was drilled in 1988.

Because hot water or steam is not readily available at the two exploratory development sites at Medicine Lake, neither the proposed Fourmile Hill site just north of the Medicine Lake summit caldera rim, nor the Telephone Flat site within the caldera can be developed economically without hydraulic fracturing through Enhanced Geothermal Systems involving "*human intervention* to *engineer* hydrothermal reservoirs in hot rocks for commercial use."[9] EGS reservoirs are made by drilling wells into hot rock and fracturing the rock by the use of acids, high pressure fluids, and other experimental means. Prior testing and exploratory

[7] http://www.eere.energy.gov/topics/geothermal.html (EGS uses acidification and/or fracturing of hot rock)
[8] Feb 7, 2012 letter from Calpine to Tim Burke, BLM, Alturas. Ultimate proposed buildout is now 480 MW compared to two projects of 49.9 gross MW at Fourmile Hill and 48 gross MW at Telephone Flat proposed in the mid-1990s.
[9] *From DOE website* http://www.eere.energy.gov/topics/geothermal.html (*emphasis added*)

drilling has resulted in 24 or more shallow temperature gradient holes and 4 deep exploration wells. The deepest well (17A6) extends to 9,629 feet depth below ground surface. To develop this geothermal resource it would be necessary to pump water from water-supply wells into the production wells and to simultaneously enhance permeability to circulate that water and recover it as steam. There are no sustainable surface water sources or shallow groundwater reservoirs from which to supply the production wells because the high regional permeability allows rapid infiltration of snowmelt that is carried into the regional groundwater system to feed the FRS.

To meet this challenge, the project proponents have proposed the injection of acids into production wells under high enough pressure to force it into clay-filled fracture systems in the hot volcanic rocks. Hydrofluoric and hydrochloric acids, often used with a bulking agent, are pumped under pressure into the wells. The basic problem is that hydrofluoric acid is extremely toxic, even at a few parts per million. Any further environmental analysis must assess risks of contamination to local and regional aquifers based on the newly proposed fivefold increase of power production.

Further research is necessary to assess possibilities of cross-contamination between the shallower groundwater with deeper zones of acid-injection and with induced fracture permeability as a result of EGS. Behavior of pressurized fluids in the thermal reservoir rocks may be different from those observed under passive conditions through exploratory wells. The contentions of the project proponents—that the proposed EGS activity is not threatening to the pristine surface aquifers because the deeper geothermal reservoir rocks are believed to be isolated from the shallower aquifers and seasonal recharge—are based on simplified groundwater models developed by Weiss and others (Weiss, 1997). Those models are often useful for reconnaissance-level initial analyses. Because the Weiss model does not fit the actual facts such as the migration of groundwater from north to south, and the chemical evidence of multiple deep sources,[10] it cannot be relied upon to support the "no harm" conclusions proposed in the 1998 FEIS/FEIRs for previously-proposed geothermal projects at the Medicine Lake Highlands.

Robert Mariner of the U.S. Geological Survey (*op cit*, 2006) points out that there are anomalies in the isotopic geochemistry of FRS water that can be explained if there is leakage (outgassing) of gas and fluids from the geothermal reservoir. Davisson and Rose (2014) also found helium values that challenge the previous EIS/EIR hypothesis of a fully-sealed barrier between the geothermal reservoir and the groundwater resources.[11] This observation also raises questions about the integrity of the areas into which acids may be pumped and potential impacts to groundwater resources.

Calpine applicants have stated (Mitch Stark, 2007, California State Water Board technical meeting, Redding, California) that the acidification will be confined to the immediate vicinity of the deep well bore-holes. If that were to be the case, such enhanced

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[10] See Davisson and Rose's (2014) *conclusions* regarding magmatic gases in the FRS spring-water "magmatic *gases* are prevalent in the spring discharge, particularly those derived from MLV recharge. From carbon isotope measurements, all spring discharges show dissolved inorganic carbon comprising 30% to 40% magmatic CO_2 contribution"

[11] Mariner explains: "A geothermal system that does not leak water or gas should have lower helium isotope compositions due to a buildup of crustal helium in the geothermal reservoir. The high value raises the possibility that there is unidentified outflow of geothermal fluid from this geothermal system." Davisson & Rose in the conclusions to their 2014 paper demonstrate that all samples prove that Mariner was correct.

permeability would not meet the needs of the project for geothermal recovery. As the DOE hydrofracturing EGS promoters point out, to be effective, well treatments must provide sustained access to a large reservoir of hot rock hundreds to thousands of feet around the production wells (DOE animation – *click figure*):
http://www1.eere.energy.gov/geothermal/egs_animation.html

FRS flows originate on the Medicine Lake Volcano

Controversy has clouded understanding of possible sources for the enormous shallow groundwater discharge of over 1 million ac-ft per year at FRS, but the work of Rose at the Livermore labs and the contemporary analysis by Davisson and Rose (2014) states: "Isotopic measurements of the 34 m^3/s discharge from the Fall River Springs of northern California indicate recharge from 50 km upgradient in high elevation regions of Medicine Lake Volcano."

Young lava flows have filled the ancestral valleys that once carried the headwaters of Fall River and today that subsurface river system emerges as a series of springs along the southern edge of some of the lava flows. High snowfall on the Medicine Lake Highlands clearly provides a significant source of the spring flow, but not from the adjacent Modoc Plateau east of MLH as previously believed. A U.S. Geological Survey report (Lowenstern et al, 1998) attempted to estimate contributions based on geographic areas and elevations of various portions of the Plateau and the Highlands. That study used the 1969 final compilation of statewide 1911-1960 California precipitation data prepared by statistical hydrologist Sol Rantz. It used ground elevation and statewide historical precipitation records to synthesize an estimate of rainfall isoheyets for the entire state based on geographic areas surrounding area-weighted precipitation data. This is an important issue that is discussed below under *Information Needs*. It is vital to update and utilize current precipitation baseline data in order to determine groundwater recharge sources as well as impacts from geothermal proposals.

Differing professional opinions on the sources for Fall River Springs' recharge bear directly on the issues of potential contamination of the FRS by geothermal exploration and production. The 1998 EIS/EIR on geothermal development speculated that the high discharge of Fall River Springs must derive from the Klamath River basin to the north or elsewhere. Davisson and Rose (2014) point out that the fundamentally different geochemistry of the more arid Klamath basin runoff is not reflected in the Fall River Spring flows. If the snowmelt in the Medicine Lake Highlands is but a small percentage of the total FRS flow or does not contribute significantly to that flow, then risks of contamination from enhanced geothermal development may be less than significant.[12] However, the water at Fall River Springs has an isotopic composition (Oxygen-18) that indicates that it comes from

[12] An analysis by John Bredehoeft in 1997 specifically addresses this issue. Groundwater hydrologist Bredehoeft concluded that probably only a small portion (diluted by 30-times) of the Fall River Springs' flow would be contaminated by a spill on the Medicine Lake Highlands. This assessment is not consistent with contemporary FRS spring water isotopic analyses or with reasonable evapotranspiration adjustments for the much more arid Modoc Plateau. Bredehoeft further assumed that Fourmile Hill was outside the FRS drainage area but newer mapping suggest this may not be entirely the case (Gannett, et al, 2010).

Medicine Lake Highlands' elevations (Davisson, 1997; Davisson and Rose, 2014; Rose,[13] 1996). Alternatively, Weiss Associates (1997) suggested that the large volume of flow at FRS implies a source that includes *a* much larger area of both high and lower elevation areas of the Modoc Plateau between MLH and the FRS about 33 miles to the south, a conclusion that we find improbable based on contemporary precipitation, soils, and vegetation data.

Determining the source of the FRS is critical to determining potentials impacts of geothermal development.

Determining the source of the FRS is critical because if we underestimate the contribution to the FRS from the Medicine Lake Highlands, we will then underestimate the impacts to those Springs from the EGS acidification. Using the limited historical precipitation data, some consultants estimate that an acid spill or shallow water contamination would only affect about 10 percent of the Fall River Spring flow, (Bredehoeft, 1997) because they incorrectly utilized the Modoc Plateau precipitation to make up a large part of the stream flow at the FRS. However, as discussed in the previous section and under *Information Needs*, the FRS originate primarily from snowmelt in the Highlands and not from the Modoc Plateau as outdated models suggested. Based on current knowledge, as much as 80% of the Fall River Springs volume can derive from snowmelt in the Medicine Lake Highlands. Further analysis of current data, more sampling along the full16 km length of the FRS, and soil moisture measurements would resolve these differences of professional opinions, and affirm the Medicine Lake Highlands as the primary origin of the FRS.

Given the magnitude and import of this resource to California's water supply, these analyses can and should be carried out and those results need to be included in any new environmental analysis.

Information Needs

Highly professional effort has gone into evaluation of controversial issues surrounding proposed development of geothermal resources at Medicine Lake Highlands, but significant uncertainties remain due to data gaps and outdated baseline information as described below. Conclusions and models will change as the results of new research and analyses are applied.

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[13] "Given the hydrogeologic configuration of the Fall River aquifer system, it appears that the Medicine Lake Volcano is the only likely source of the volcanic CO_2. Measurements of dissolved helium gas in the Fall River Springs (unpublished data) also show modest enrichments in mantle derived ^{3}He that is likely to have originated from the volcano. In general, the carbon and helium isotope data for the Fall River Springs are consistent with a recharge source on Medicine Lake volcano. The dissolved CO_2 and helium are most likely introduced to the shallow groundwater flow system as diffuse gas emanations from depth." *Tim Rose, – Lawrence Livermore Labs letter report, 20 Oct., 2006*

"Carbon-14 analyses of the Fall River samples indicate that at least 27% of the dissolved inorganic carbon in the springs was derived from a volcanic CO_2 source. This requires that the groundwater supplying flow to the Fall River Springs must originate from an area where magma degassing is actively occurring. Given the hydrogeologic configuration of the Fall River aquifer system, it appears that the Medicine Lake Volcano is the only likely source of the volcanic CO_2." *Op cit* Rose, *2006 letter report*

Oversimplified model of the hydrogeologic system leads to unreliable results

The applicants for the original 48 MW CalEnergy development at the Telephone Flat site retained Weiss and Associates to evaluate geologic and hydrologic issues and risks (Weiss, 1997). Unfortunately, that firm proposed a greatly oversimplified model of a three-compartment hydrogeologic system that proposed fully isolated groundwater components within the Medicine Lake caldera and mistakenly attributed a significant source of FRS flow to the Modoc Plateau. This model was also used for the proposed development at the Fourmile Hill site. The net result was that the MLH shallow aquifers were not widely considered as a water source of FRS. This simplification by the Weiss Associates report avoided the need to evaluate cross-contamination issues and clouded FRS spring-water source evaluation requirements.

With the current fivefold increase in proposed levels of development, the Weiss report again needs to be closely scrutinized. In fact, it is clear to this author that the Weiss authors realized that their simplified model of sources of water sufficient to provide the observed Fall River Springs flow was doubtless incorrect. Every statement that estimates contributions of precipitation to groundwater and thus to FRS flows is qualified by a statement that their numeric calculations do not account for unknown evapotranspiration (ET). Weiss ultimately attempted to qualify their estimates by taking an average value for ET of 36 cm (14-inches per annum) based on data for Newberry Volcano 166 miles north in Oregon. But of course it is not the average ET, but the difference between MLH surface ETs and lower-elevation Modoc Plateau conditions that is critically important for apportioning sources of the FRS flows.

Indeed, those concerns that are implied in the final Weiss Associates report are fundamental to the analyses of potential threats to the Fall River Springs component of California's water supply. The 1998 USGS Open File Report 98-777 (Lowenstern et al, 1998) included a component on hydrology that was considered as a basis for geothermal development impact risk analyses (Bredehoeft, 1997; Weiss, 1997, etc.). That report states:

"Our calculations show that precipitation input to Basin VII[14] is about 140% of the amount that discharges at the Fall River Springs. Over 70% of this precipitation would have to supply groundwater recharge to be the sole source of water to the springs. This value is quite high, implying that some other basins supply some recharge water.

The Medicine Lake Caldera region (Basin I) receives only 4.5% as much precipitation as Basin VII and 6% of that of the Fall River Springs. Basin I can only be a minor source of water to the Springs."

The USGS analysis was a simple extrapolation from the Rantz 1969 rainfall isoheyets, and suffers the same shortcomings as the earlier estimates, i.e., Rantz analyzed precipitation, which is not uniformly proportional to groundwater recharge. The 1998 USGS Lowenstern study did not include any estimation of potential evapotranspiration (ET) or differences in ET with elevation, aspect, soil-type, or vegetation and snowmelt characteristics. Their work implies that all the Rantz isoheyetal geographic information is

[14] The Basin VII geographic area includes the more arid south and southwest sides of the Medicine Lake Highlands that they classed as the Fall River Graben. It includes both high and low elevation south-facing slopes and land areas overlying the FRS sources. Basin I is only the central mountain-top caldera itself.

directly proportional to values for groundwater recharge. This conclusion is simply not supported by the data they present.

Newly available data needs to be incorporated into the analyses

To go forward with a current and more accurate assessment of the potential risks and impacts of geothermal development in the Medicine Lake Highlands, the recharge of water to the various potential sources of Fall River Springs needs to be estimated using sound science. First, the Rantz data that was based on a single precipitation station in the Highlands and limited stations farther east on the Modoc Plateau needs to be updated. We now have 10 or more climate stations that have usable data that can be calibrated against the one long-term station. This may provide enough data to conduct multiple-regression time-lagged analyses of historic Fall River flow versus prior seasonal snowfall.

Second, federal agencies have begun to evaluate soil moisture conditions to try to conduct stand conversions of brush and scrub conifer woodlands to range lands east of the MLH on the Modoc Plateau. These soil data include rooting depths of vegetation and are relevant to an understanding of the effectiveness of snowmelt recharge in the area.

Third, Gannett in his 2010 USGS monograph on the Upper Klamath watershed groundwater resources believes that the northward flow of groundwater off the Medicine Lake Highlands is believed to turn at the base of the volcano and flow east and then south down gradient to feed Fall River Springs (Gannett et al, 2010, see Fig 21, p. 45). This suggests that the Weiss and Associates Figure 14 (groundwater flow directions found in the Telephone Flat FEIS/FEIR in Technical Appendix A) may have been misleading. Bredehoeft reproduced the Weiss figure as his Fig. 6.

And fourth, although both Davisson's and Rose's 1997 Lawrence Livermore National Laboratory publication and the more current 2014 study draw similar conclusions, the current study differs in several ways: 1) there is an analysis of noble gases in the 2014 study that was not in the 1997 publication that gives further credibility to the MLV as the source of the FRS; 2) the 2014 publication is 'peer reviewed', while the first was an 'in-house' publication with limited circulation; 3) the age of the water is delineated in the 2014 study as a range; 4) the 2014 publication was more inclusive of relevant data such as Mariner's 1998 data and other later publications such as Palmer et al, 2007.

Vegetation as an indicator of annual precipitation

The geographic areas of presumed rainfall interpreted by Lowenstern, et al, in 1998 and 2004[15] do not reflect relative proportions of precipitation that may recharge the groundwater. The primary issue here is the proportion of the annual precipitation that infiltrates through the vadose (unsaturated) groundwater zone to recharge water tables. Using precipitation and soil data and observed plant cover, reasonable analysis suggests a different conclusion than Lowenstern, et al 1998, in that much of the southern and eastern

[15] Lowenstern, J.B. et al, 1998 revised 2004, USGS Open File Report 98-777, 3-Dimensional Visualization of the Medicine Lake Highland, CA: Topography, Geology, Geophysics, and Hydrology http://pubs.usgs.gov/of/1998/of98-777

Modoc Plateau in many water years contributes little or no recharge to the shallow water tables that contribute to both upper Klamath River and Fall River flows. This is so in both the arid shrub-covered and juniper-covered portions of the Plateau.

Plant roots tell the story, and the distribution of plants reflects the soil moisture regimes, which in turn correlate with the frequency of years when there is net downward-percolation of precipitation through the vadose zone to supply net additions to groundwater. The high elevation and high winter snowfall accumulation red fir zone in the Highlands cannot be lumped with the lower elevation and lower precipitation juniper and brush areas to calculate areas and volumes of potential snowmelt recharge. Western Juniper tree-cover is associated with decreases in late summer soil moisture because the junipers are more tolerant than were native grasses of low-soil-moisture conditions.[16] Current federal efforts to restore grasslands and sage-steppe seek to increase soil moisture holding capacity in the soils but do not propose significant increases in regional water tables or through-recharge. In addition, a study of Spotted Owl habitat in the MLH (Buettner, 2010) used distributions of tree species and their characteristics as well as other vegetation types that may be directly pertinent to the distribution of areas of high snow accumulation and recharge.

Snowfall studies point to MLH as the primary source of Fall River Springs

Further, and in contrast, the Medicine Lake Highlands is an area of snowfall-dominated precipitation. Snowmelt recharge under a typical spring snowpack in those highlands with very porous volcanic soils probably contributes almost 80-90 percent of its snow-water equivalent directly to the vadose zone from where it percolates down to maintain regional groundwater tables as well as supports deeper-rooted conifers such as Red Fir.[17] It follows from these observations that less than 20% of the FRS flows may originate as precipitation on the Modoc Plateau, while as much as 80% of that in the Medicine Lake Highlands may recharge in most water-years to feed directly to Fall River Springs. Thus the water balance models used to evaluate risks to surface water quality in the Sacramento River system is not as Weiss and Bredehoeft postulated. In summary, a current and more accurate assessment of the potential risks and impacts of geothermal development at Medicine Lake needs to be formulated using sound science to estimate the recharge of water to the various potential sources of Fall River Springs.

The high risks of EGS hydrofracturing

A further area for added investigation is the issue of Enhanced Geothermal Systems (EGS). If, as stated by the applicants in their applications to the State Water Resources Control Board for use of acids to enhance permeability, this process is intended to provide substantial improvements in fluid circulations in the deep hot rock zones, then the appropriateness of this treatment needs to be more thoroughly evaluated.

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[16] Burke, Tim, 2011, Sage Steppe Restoration on the Modoc Plateau
http://www.blm.gov/wo/st/en/info/history/sidebars/ecosystems/sage-steppe_restoration.html

[17] This conclusion is based on personal soil moisture and ground freezing research over the past 45 years in Eastern Sierra Nevada volcanic areas.

The use of hydrofluoric-based acidification fluids poses inherent risks to surface and ground waters related to transportation and application-handling. With acid substances transported overland, and with acidification fluids passing through potable groundwater reservoirs that then discharge rapidly into regional and statewide water systems, these activities create a risk that is far greater than simple leakage of underground storage tanks at local gasoline stations. You cannot recapture these toxic substances by simply pumping them out of the ground or the Sacramento River after a spill or leak.

Research Recommendations:

The following summarizes minimal research and information needs that are necessary to resolve present critical controversies and to provide an adequate baseline assessment *before* preparation of any EIR/EIS on the geothermal development in the Medicine Lake Highlands.

A. Evaluate the volumes of recharge that can supply Fall River Springs to assess sources and risks:

i) Use current BLM/USFS sage-steppe grasslands restoration efforts to assess volumes of soil water that may reach water tables on the Modoc Plateau restoration sites.
ii) Map red-fir/mountain hemlock distribution in the Medicine Lake Highlands and use elevations of these trees to assess snowpack recharge. Red fir is intolerant of frequent ground freezing and its distribution thus reflects greater seasonal snow depths that protect the ground from freezing. Also, the lowest elevations of red fir can be correlated with snow-water content to more accurately estimate geographic areas of snowmelt recharge.
iii) Monitor wells in the Highlands and lower Modoc Plateau elevations where vadose zone recharge may supply saturated-zone groundwater and compare that to regional precipitation records to evaluate frequency-magnitude relationships.
iv) Assess all available precipitation and snowmelt data (include new USFS, PG&E and CA State Snow Survey data) and weight it by results of (i) to (iii) above to calculate more accurate potential precipitation recharge over a 50-year possible geothermal production period.
v) Conduct statistical analyses to separate seasonal recharge from regional base-flow water sources to estimate impacts of climate change, forest health and fire incidents, and potentials for changes in volcanic activity of the Medicine Lake Volcano area on FRS flows.
vi) Include new information from the USGS monograph on the Upper Klamath (see Marshall W. Gannett, et al: *Ground-Water Hydrology of the Upper Klamath Basin, Oregon and California* USGS Scientific Investigations Report, 2010) and the 2014 report by Davisson and Rose.

B. Evaluate sources and volumes of groundwater available for geothermal drilling and steam production.

i) Conduct drawdown tests of Telephone Flat and Fourmile Hill groundwater sources to evaluate volumes and sustainability of water resources for 50 or more years of full geothermal production at the proposed 480 MW level.
ii) Assess potential impacts of withdrawal of those water volumes on local water supplies, ecosystems, and recharge.

iii) Update the 1995 tabulation of wells supplied in Weiss, Table 6 (1997) and verify depths to top of lowest seasonal water table. The 1995 tabulation is not useful for assessing available water for geothermal development.

C. Evaluate the technical assessments of contamination possibilities of the Medicine Lake Highlands, Modoc Plateau, McCloud River, and Fall River Springs.

i) Evaluate the technical assessment of possibilities of contamination of the shallow MLH aquifers as compared to Modoc Plateau shallow aquifers (Weiss's HU1 vs. HU2) to resolve the Rose, Davisson, Mariner, and Lowenstern research questions. Those latter research studies were primarily based on helium and carbon-dioxide isotopic analyses of Medicine Lake Highlands and Fall River Springs waters. Resolve whether the observed anomalies in isotopic composition of gases and water in and on the Highlands and Fall River Springs indicate possible active (contemporary) exchanges between the geothermal reservoir and surface aquifers as proposed by Davisson and Rose in 2014. Resolve whether those exchanges are episodic and/or associated with seismic activities or the many inferred local fault-controlled fracture systems (Ciancanelli, 1983) and resolve whether they are the result of leakage from the "isolated" geothermal reservoir. *See footnote 13.*
ii) Reevaluate the Hydrodynamics Group (Bredehoeft, 1997) model of potential dilution of spilled or leaked EGS fluids on long-term (90 year [40-year travel time + 50-year production window]) Fall River spring flows. Consider Fourmile Hill as <u>within</u> the recharge area for FRS. A contamination model should also evaluate the proposed 480-megawatt level of development and all likely risks of accidents including years of heavy winter snowfall and site inaccessibility.
iii) Existing sampling should be augmented to meet the needs of these unresolved geochemical issues, including broader sampling along the 16 km linear extent of the FRS to determine variations in age and pathways. In addition, a strongly recommended research project would involve understanding where helium-3 and helium-4 occur in different environments, in order to determine the source of the water, and the potential mixing of the deep geothermal resource and the groundwater aquifer. This study needs to be undertaken by a full laboratory facility.
iv) Consider both liquid- and vapor-dominated geothermal reservoir systems.

D. Evaluate possibilities of cross-contamination between deeper zones of acid-injection and/or induced fracture permeability to the shallower groundwater aquifers and the Fall River Springs.

i) Evaluate the implication of strategies to maintain geothermal production from a declining thermal resource on the shallow ground water aquifer. This research would look at the risks associated with developments in various locations within the caldera as well as the depth of induced fracturing or enhanced permeability, especially on the south and eastern flanks of the volcano where FRS recharge is probably most critical. This effort would probably require drilling new monitoring wells inside and outside the caldera rim and the use of tracers to evaluate groundwater movement.
ii) Expand monitoring to the easternmost tributaries of the McCloud River system on the western flank of Medicine Lake Volcano to establish baseline conditions for the McCloud watershed.

E. Develop a regional water balance model that includes drought periods and above normal snowfall periods and encompasses various source area concepts (FRS sources, eastern McCloud River sources, maximum Modoc Plateau contributions; minimum Modoc Plateau contributions, etc.)

i) Utilize all regional precipitation data

ii) Accommodate evapotranspiration and evapotranspirative demand for various sites as appropriate
iii) Utilize soils (substrate permeability, water storage capacity, texture) and vegetation cover data
iv) Evaluate rapid vs. seasonal snowmelt and rain-on-snow events
v) Test water balance model against historical hydrography of Fall River and other gauged sites.
vi) Include new information from USGS monograph on the Upper Klamath (see Marshall W. Gannett, et al: *Ground-Water Hydrology of the Upper Klamath Basin, Oregon and California.* USGS Scientific Investigations Report, 2010).

F. To protect both local surface water resources such as Medicine Lake, Paynes Springs, Bullseye Lake and Blanche Lake as well as the shallow groundwater resources that supply Fall River Springs and the eastern McCloud tributaries it will be necessary to devise and implement a careful and *thorough pre-project monitoring plan* suitable for the newly proposed 5-fold increase to 480 mw of geothermal development. This development scenario should accommodate Enhanced Geothermal Systems and other production-enhancing strategies in a low-permeability poor-circulation geothermal resource environment.

i) The monitoring program must identify, evaluate and protect surface and shallow groundwater resources within the Caldera from leakages and contamination, as well as the Fall River Springs, which could take 50 or more years to detect.
ii) The monitoring plan would evaluate and learn from monitoring well failures elsewhere such as Coso Hot Springs.
iii) Monitoring wells should be designed to withstand corrosive hot (>250º C) conditions at depths appropriate for protecting surface water features at the elevations of FRS and above. Monitoring systems must operate in areas of deep snowfall and poor seasonal surface access without mechanical failures. At depth they must reliably withstand high temperatures with component level reliability in high-pressure/high-corrosivity environments, and provide reliable remote telemetered measurement/logging systems.

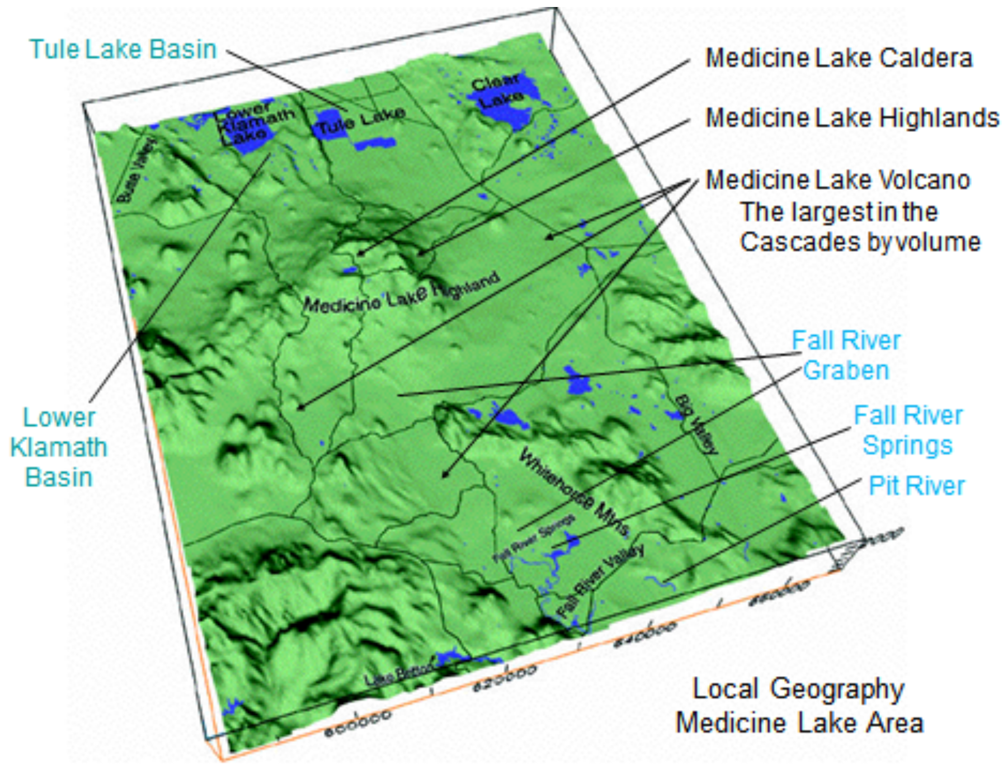
Conclusions:

Adequate baseline information is not presently available to allow preparation of an EIR/EIS for the expanded 480 MW scope of the currently proposed Medicine Lake geothermal project. Direct, comprehensive, and straightforward analysis is needed to define the contributions of various geographic areas to flows at the Fall River Springs (FRS), the headwaters of the eastern McCloud River, and to more accurately model the flow and volume characteristics of the underlying aquifer or aquifers of the MLV.

More sophisticated and potentially controversial is the resolution of differences of professional opinions surrounding the geochemistry of gases and fluids in MLH groundwater and FRS. The implications of these observed anomalies upon potentials for contamination of the FRS need to address the issues raised by Bredehoeft of potential dilution of effects of potential spills of hydrofluoric acid or other substances if they are stockpiled and handled at the ground surface and injected at depth to facilitate EGS recovery. The issue of vapor-phase leakage from the geothermal reservoir needs to be readdressed in light of the Davisson and Rose contemporary work.

The magnitude of the watershed resources in the Medicine Lake Highlands and the potential threats to the water quality of an aquifer of statewide importance requires thorough and unbiased environmental analyses and the assessment of tradeoffs before committing the site to geothermal development.

Figure 1



Base map from USGS Open File 98-777

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